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PATENT SPECIFICATION

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(54) APPARATUS FOR SEQUENTIALLY COMBINING PULSED BEAMS OF RADIATION

(71) We, JERSEY NUCLEAR—AVCO ISOTOPES INC. a Corporation of the State of Delaware, United States of America of 777 106th Avenue Northeast, Bellevue, Washington 98004, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a system for combining beams of pulsed radiation.

In systems employing pulsed laser radiation, it is often desirable to employ a higher repetition rate for the pulsed laser radiation than is commonly available from a single component laser. Techniques frequently employing rotating optics are known which permit the sequential combination of pulsed laser radiation beams onto a single common axial beam. These and related techniques are represented by U.S. patents 3,543,183; 3,310,753; 3,541,468; 3,568,087.

In one application for high pulse rate in laser radiation, isotope separation is accomplished by isotopically selective laser photoionization in a high flow rate environment of plural isotope types. An example of such a use is described in U.S. patent 3,772,519. For such an application of laser enrichment, it is typical to find laser beam paths which extend over substantial distances and which nevertheless require a precise and nonvarying angular orientation and superposition of several different frequency laser beams. Laser pulse durations may typically exist in the range of a substantial fraction of a microsecond for this use. Where rotating optics are employed to receive each sequential pulse from respective plural lasers in order to combine them at a unitary path, the angular motion of these optics will result in an angular motion of the combined laser beams. This motion may appear as a beam deflection as well as a rotation of the plane of deflection from pulse to pulse. In applications of laser enrichment which require the consistent illumination of a predetermined channel throughout the environment of isotopes to be separated, such angular motion in the radiation is intolerable.

According to the invention there is provided a system for combining beams of pulsed radiation comprising:

a plurality of pulsed radiation sources for providing spatially separate beams of radiation pulses in a sequence, said radiation pulses each having a finite time duration and being distributed about an axis;

means for receiving the sequence of spatially separate beams of radiation pulses distributed about said axis to direct said separate beams of radiation pulses along a generally common path;

said means for receiving said sequence of beams of radiation pulses to direct them along a generally common path including rotating means for directing the pulsed beams along said common path substantially without dynamic angular variation in the pulsed radiation beams throughout the finite duration of each radiation pulse.

In preferred embodiments of the present invention, systems are provided which correct for the angular deflection in a composite beam of pulsed laser radiation resulting from the sequential superposition of plural, sequentially pulsed laser radiation beams onto a unitary path.

Continuously rotating optics may typically be employed to combine the pulsed output of an array of laser sources. In one embodiment, a set of compensating optics are added to eliminate the angular variation or deflection resulting from the finite duration of each laser pulse and corresponding travel of the rotating optics. In a further embodiment, a particular beam combination system itself eliminates

the angular variation resulting from the rotational movement of the combining elements.

In such embodiments, a small, and often negligible amount of lateral beam displacement without angular variation can result from the combining system. An additional optical system is optionally employed to correct for this displacement where desired.

In addition, there are disclosed systems employing several stages of beam combining units of the type described above to achieve an effective increase in laser pulse repetition rate on the order of several magnitudes using either low repetition rate lasers or initially high repetition rate lasers.

The invention will be further described, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 illustrates one form of pulsed laser beam combining means without compensation for angular beam motion;

Fig. 2 illustrates a further form of pulsed laser beam combining means without compensation for angular beam motion;

Figs. 3A—3B illustrate the angular motion resulting from uncompensated laser beam combining systems;

Fig. 4 illustrates a first embodiment for a pulsed laser beam combining system compensated for angular motion;

Fig. 5 illustrates a further form for a pulsed laser beam combining system compensated for angular motion;

Fig. 6 illustrates a modification to the system of Fig. 5;

Fig. 7 illustrates a technique for combining a plurality of laser outputs in several stages to provide a greatly increased pulse rate in the resultant, combined output beam;

Fig. 8 illustrates a further multiple stage technique for combining a plurality of pulsed laser beams to provide an increased output rate; and

Fig. 9 illustrates an optic system for use in the embodiments of Figs. 4 and 5 for compensating for beam displacement in the beam of combined laser radiation pulses.

In the preferred embodiments, systems are described for increasing the effective pulse rate of a pulsed laser system by combining, in sequence, the output of a plurality of pulsed lasers into a common beam of pulse rate which is increased by the number of lasers employed in the system. A compensation system is employed to correct for dynamic variations in angle of the output beam resulting from movement of the combining optics during each pulse of laser radiation. While of particular utility in a laser system, however, the invention may be employed for combining any pulsed beams.

In particular, with reference to Figs. 1 and 2, there is shown apparatus which operates to combine the output of a plurality of sequentially pulsed lasers into a single pulsed beam with a pulse repetition rate increased by the number of lasers employed in the system. Particularly, with regard to Fig. 1, there is shown an array of lasers 12 positioned to radially direct their output radiation toward a central point for application to a rotating reflecting surface 14, typically a prism. The radiation pulses from the lasers 12 are synchronized with respect to a drive mechanism 16 for the reflector 14 by a synchronization or distributor system 18 so as to provide an output beam 20 upon a common axis. Accordingly, the reflecting surface 14 is directed to receive each beam of radiation from the respective laser systems 12 at the particular moment when that beam will be reflected along the path 20.

In Fig. 2, a similarly functioning system is disclosed employing a rotating cylinder 22 which has a plurality of mirrors 24 placed at staggered positions around the outer circumference thereof at axially displaced locations and directed to reflect laser radiation from a bank of parallel lasers 26 onto a common output path 28. A synchronization system 30 is operative with a drive mechanism 32 for the cylinder 22 to ensure that each laser 26 is fired at the instant when its corresponding mirror 24 is aligned to reflect radiation onto the common axial path 28.

Figs. 3A and 3B illustrate the character of the dynamic angular variation in the beams 20 or 28 resulting from the finite motion of the reflecting surfaces 14 or 24 during a cycle of radiation in the lasers 12 or 26. In Fig. 3A, this effect is illustrated for the Fig. 1 system. Not only does radiation beginning, for example, at a point 34 and terminating at a point 36 during the pulsed duration for a particular laser 12, traverse an angle θ, but the orientation of the angle θ is seen to vary with the position of the particular laser 12 fired among positions 38, 40 and 42, for example, shown in Fig.1.

In lasers used for isotopically selective photoionization, the duration of output radiation in each laser pulse may approach a significant fraction of a microsecond thereby giving to the angle θ a significant and relatively large magnitude over the pulse duration. Such angles can approach a substantial fraction of a degree and can significantly vary the position of the laser radiation in the isotope separation chamber of the type described in the above-referenced U.S. patent 3,772,519. With respect to Fig. 3B, the phenomenon of varying angle is also shown as it corresponds to the Fig. 2 system but without the added complexity of a variation in the orientation of the angle θ.

A system which is operative to compensate for the angular deflection and variation in orientation shown in Figs. 3A and 3B, is illustrated in Fig. 4. As shown there, a radial array of laser sources 44 (or other pulsed beam sources) direct their respective output beams in pulsed sequence, toward a rotating, reflective surface 46. The surface 46, typically a prism, will be rotating with an angular velocity, ω . The reflecting surface 46 is rotated by a drive system 48 which cooperates with a synchronization system 50 to energize each laser 44 at the appropriate moment for its pulse of radiation to be reflected by the surface 46 onto a common vertical path 52 as has been described above.

The laser radiation in path 52 is directed toward an optical system 56 having an odd number of reflecting surfaces for which the preferred embodiment is a "K" mirror. The "K" mirror 56 is counter-rotating with respect to the reflecting surface 46 at half its angular rate of $\omega/2$. The rotation of "K" mirror 56 is synchronized with the rotation of reflecting prism 46 by a further drive mechanism 54. The effect of the counter-rotating "K" mirror 56 is to compensate for the effect of rotation of the orientation of the deflection angle in the output radiation as shown in Fig. 3A. Partially corrected radiation leaving the "K" mirror system 56 is incident along a common axial radiation path 58 to a corotating array 60 of deflecting surfaces driven by a drive mechanism 62 in a direction counter to the rotation of the "K" mirror 56, angled preferably at 45° to the incident radiation and of a number equal to twice the number of lasers 44. This corotating array reflects each pulse of laser radiation onto a common output beam path 66 and operates to all but eliminate the angular deflection in the output beam as indicated in Figs. 3A and 3B. The combined output beam on path 66 will then be nearly free of dynamic deflection and exhibit only a slight displacement. The residual deflection is typically, or may be kept, insignificant for the disclosed application. In place of "K" mirror 56 a "dove", "reversion" or Pechan prism or other suitable optics may be employed.

For reducing the dynamic variation in the Fig. 2 system, only the array 60 needs to be employed. The Fig. 2 system is very suitable for combining a limited number of laser beams with several mirrors per beam placed circumferentially around the cylinder.

An alternative system is illustrated in Fig. 5, wherein a similar radial array of lasers 68 is provided with the radiation thereof directed towards a central point. Surrounding that central point is an array 74 of stationary mirrors 70 which are angled at 45° to reflect each sequential pulse of radiation from the lasers 68 onto plural paths 75 coaxial to a central axis 72 for the mirror array 74. Each path is equidistant from the axis 72 and equally spaced around an imaginary cylinder about that axis. The array 74 is a convenience for laser placement. It is to be understood that any other system or arrangement which provides cylindrical or conical symmetry in the laser beam path is equivalently useable.

The radiation in the path 75 is applied to a rotating solid rhombic prism 76 which has first and second parallel reflecting surfaces 78 and 80 on opposite edges. The first reflecting surface 78 is oriented to intercept each pulse of radiation from reflecting surfaces 70. The axis of rotation for the rhombus 76 is coincident with the axis 72 and passes through the second reflecting surface 80. A common axis output beam path 82 is provided after reflection of the input beam from surfaces 78 and 80. The combined beam path 82 is free of the angular deflection represented in Figs. 3A and 3B. A drive system 84 for the rhombic prism 76 cooperates with a synchronizer 86 which activates each of the lasers 68 such that the radiation from each reflecting surface 70 is appropriately timed to be centered upon the first reflecting surface 78 in the rhombic prism 76.

A preferred embodiment is represented by Fig. 5 and employs parallel reflecting surfaces 78 and 80 within the rhombic prism 76. It is, nevertheless, possible to use nonparallel reflecting surfaces as illustrated in Fig. 6. The advantage of employing nonparallel reflecting surfaces as illustrated in Fig. 6 is a minimization of the rotating mass of the rhombic prism. As shown in Fig. 6, incident radiation along paths 90 from each of the plural radially disposed laser systems strike a corresponding mirror 92 in an array 94 similar to the array 74. The mirrors 94 are angled more obliquely to the incident radiation so as to direct the reflected radiation not along a coaxial path but inwardly in generally conical symmetry toward a rotating prism 96, and a reflecting surface 98 on the prism 96. Radiation reflected from the surface 98 is directed at an angle towards a further reflecting surface 100 through the prism 96 which, in turn, reflects the laser pulse onto a common central axis 102. The angles of the mirrors are selected to provide a common path, although complete freedom of dynamic variation is not possible. Similar rotational drive and laser synchronization elements are employed in the Fig. 6 embodiment as shown in Fig. 5.

If each individual laser system employed for the initial laser pulse has a typical maximum repetition rate of 500 pulses per second and it is desired to have an ultimate,

effective pulse repetition rate approaching 50 KH_z, then a total of 100 lasers must be synchronously combined. For that purpose, it may be desirable to use several stages of combination as illustrated in Fig. 7. As shown there, a plurality of lasers 104 are divided into groups of, for example, 10, with a possible 10 groups in order to make a total of 100 lasers. Each group of 10 lasers applies its sequentially pulsed radiation to an optical combining system 106 which may employ a combining technique similar or identical to that illustrated in Figs. 4 and 5. Each of the combining systems 106 will provide a unitary, common axis output which is, in turn, provided to a further combining system 108 which may be also similar to those shown in Figs. 4 and 5. A synchronization system 110 operates to control each of the lasers 104 in conjunction with drive mechanisms 112 and 114 for each of the combining systems 106 and 108. In particular, each pulse of radiation from a system 106 will preferably be timed to occur once per revolution in the rotation of the combining mirror in the combining system 108. As a result, the combining system 108 will operate with a rotational velocity ten times greater than that for the combining systems 106. As a general rule then, the rotational speed for the combining mirrors in any of the systems of Figs. 4, 5, 6 or 7 will correspond to the repetition rate of pulses on each individual laser input path.

It is alternatively contemplated to activate each laser in a first stage combining system 106 sequentially before activating a laser in the next first stage combining system 106.

In applications requiring extremely high frequency output pulses, for example, on the order of over 50 KH_z repetition rates, it may be desirable or necessary instead of employing a multi-staged combining system as illustrated in Fig. 7 to employ a single combining system with up to 100 incident laser radiations but with a relatively low pulse repetition rate in each incident laser beam and correspondingly low angular rotation rate for the combining mirror.

With high repetition rate lasers, for example lasers having pulse rates on the order of 4,000 KH_z, a system as illustrated in Fig. 8 may be employed. As shown there, high repetition rate lasers 116 are arrayed to direct their output radiation, in timed sequence, to decombining systems 118. Decombining systems 118 correspond to the combining systems illustrated in Figs. 4 and 5 with the input and output radiation beams interchanged. The decombining systems 126 distribute the high repetition rate pulses from the lasers 116 onto a plurality of, for example, 10 independent radiation paths 120, each with a lower pulse repetition rate, in this case by a factor of 10. This plurality of radiation paths may then be combined in a single combining system 122 having a rotational mirror velocity substantially lower than would be required to combine the outputs of lasers 116 separately. A synchronizer 124 operates with drive mechanisms 126 and 128 for the decombining and combining systems respectively to ensure the appropriately timed activation of lasers 116 in a manner known in the art.

In all cases of Figs. 1, 2, 4, 5, 6, 7 and 8, the relationship between the diverse drive mechanisms may be electronic or mechanical as through gears. Similarly, the indicated reflecting surfaces may be either silvered exterior mirror surfaces or internal prism reflecting surfaces as may be desired.

Finally, the combined pulse output beams of Figs. 4 and 5 with the increased repetition rate, while full or partially corrected for dynamic angular deflections and rotations in orientation during each radiation pulse, will experience a slight translational shift or displacement dependent upon the distance between the reflecting surfaces 46 and 64 in Fig. 4, or 78 and 80 in Fig. 5. While this may typically be minimized to a negligible point, an optical system is illustrated in Fig. 9 which compensates for this translation. In Fig. 9, a plane parallel refractive plate 130 is wobbled in synchronism by a driver 134 with the rotation of the combining optics at a rate and magnitude which essentially translates the incident beam onto a parallel output path which overcomes the amount of displacement of the incident radiation over the duration of each laser pulse. To ensure the proper orientation of the plate 130, it is rotated within a cylinder 132 so that the effective axis of rotation or wobble of the glass 130 is perpendicular to the plane of input radiation displacement. It is to be noted that the use of synchronously driven optical elements of other types may be alternately employed to compensate for the same displacement.

WHAT WE CLAIM IS:—

1. A system for combining beams of pulsed radiation comprising:

a plurality of pulsed radiation sources for providing spatially separate beams of radiation pulses in a sequence, said radiation pulses each having a finite time duration and being distributed about an axis;

means for receiving the sequence of spatially separate beams of radiation pulses distributed about said axis to direct said separate beams of radiation pulses along a generally common path;

said means for receiving said sequence of beams of radiation pulses to direct them along a generally common path including

rotating means for directing the pulsed beams along said common path substantially without dynamic angular variation in the pulsed radiation beams, throughout the finite duration of each radiation pulse.

2. A system as claimed in claim 1 wherein: said means for receiving said beams to direct them along said common path includes a plurality of reflecting surfaces with at least one of said reflecting surfaces included generally in said common path.

3. A system as claimed in claim 2 wherein said rotating means includes means for rotating said plurality of reflecting surfaces generally about said common path.

4. A system as claimed in claim 2 wherein: said plurality of reflecting surfaces comprise first and second reflecting surfaces in general facing relationship; and

means are provided for rotating said first and second reflecting surfaces in said generally facing relationship about an axis;

said axis passing through said second reflecting surface;

said rotating means including means for sequentially positioning said first reflecting surface in the path of each beam of pulsed radiation during the pulse of radiation in that beam;

said first reflecting surface being oriented to reflect that beam toward said second reflecting surface for further reflection onto said common path.

5. A system as claimed in claim 4 wherein said first and second reflecting surfaces are parallel planes.

6. A system as claimed in claim 4 wherein: the distribution of the plural beams of radiation pulses is conical about said axis; and

said first and second reflecting surfaces are in planes inclined to each other at a predetermined angle.

7. A system as claimed in claim 1 wherein said means for receiving the sequence of radiation pulses along spatially separate beams includes:

an optical system of rotating optical elements operative to combine the sequence of spatially separate beams onto said generally common path and providing an angular variation in radiation along said common path during each pulse of radiation along the common path; and

rotating optical means responsive to the pulses of radiation along the common path to substantially reduce the angular variation of the radiation pulse along said common path.

8. A system as claimed in claim 7 wherein: the angular variation in the radiation pulses along said common path include an angular deflection; and

said means for reducing the angular variation includes a rotating reflecting surface for reducing the angular deflection.

9. A system as claimed in claim 7 wherein: said angular variation in the beam of radiation pulses along said common path includes a dynamic angular deflection and a rotation from pulse to pulse in the plane of the angular deflection; and

said means for reducing the angular variation includes:

means responsive to radiation along said generally common path for reducing the rotation in the plane of the angular deflection; and

means for reducing the angular deflection in the pulses of radiation along said common path.

10. A system as claimed in claim 9 wherein:

said means for reducing rotation of the plane of angular deflection includes an optical system having an odd number of reflecting surfaces in the path of the radiation pulses along said common path, said optical system with an odd number of reflecting surfaces rotating with a first characteristic; and

said means for reducing angular deflection includes at least one reflecting surface rotating with a second characteristic in the path of radiation along said common path.

11. A system as claimed in claim 1, wherein there is provided

means operative in association with said receiving means for reducing the dynamic angular variation of the radiation along said generally common path during each pulse of radiation.

12. A system as claimed in claim 11 wherein said receiving means includes an inclined rotating reflecting surface operative to receive each radiation pulse from an array of said plurality of radiation sources.

13. A system as claimed in claim 12 further including a counter-rotating optical system positioned along said generally common path, said counter-rotating optical system having an odd number of reflecting surfaces for the pulses of radiation along said common path.

14. A system as claimed in claim 13 wherein said counter-rotating optical system includes a "K" mirror.

15. A system as claimed in claim 13 wherein said counter-rotating optical system includes a "dove" prism.

16. A system as claimed in claim 13 wherein said counter-rotating optical system includes a "reversion" prism.

17. A system as claimed in claim 13 wherein the rate of counter-rotation of said optical system is at one-half the rate of rotation of said reflecting surface.

18. A system as claimed in claim 11

1502801 COMPLETE SPECIFICATION

3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

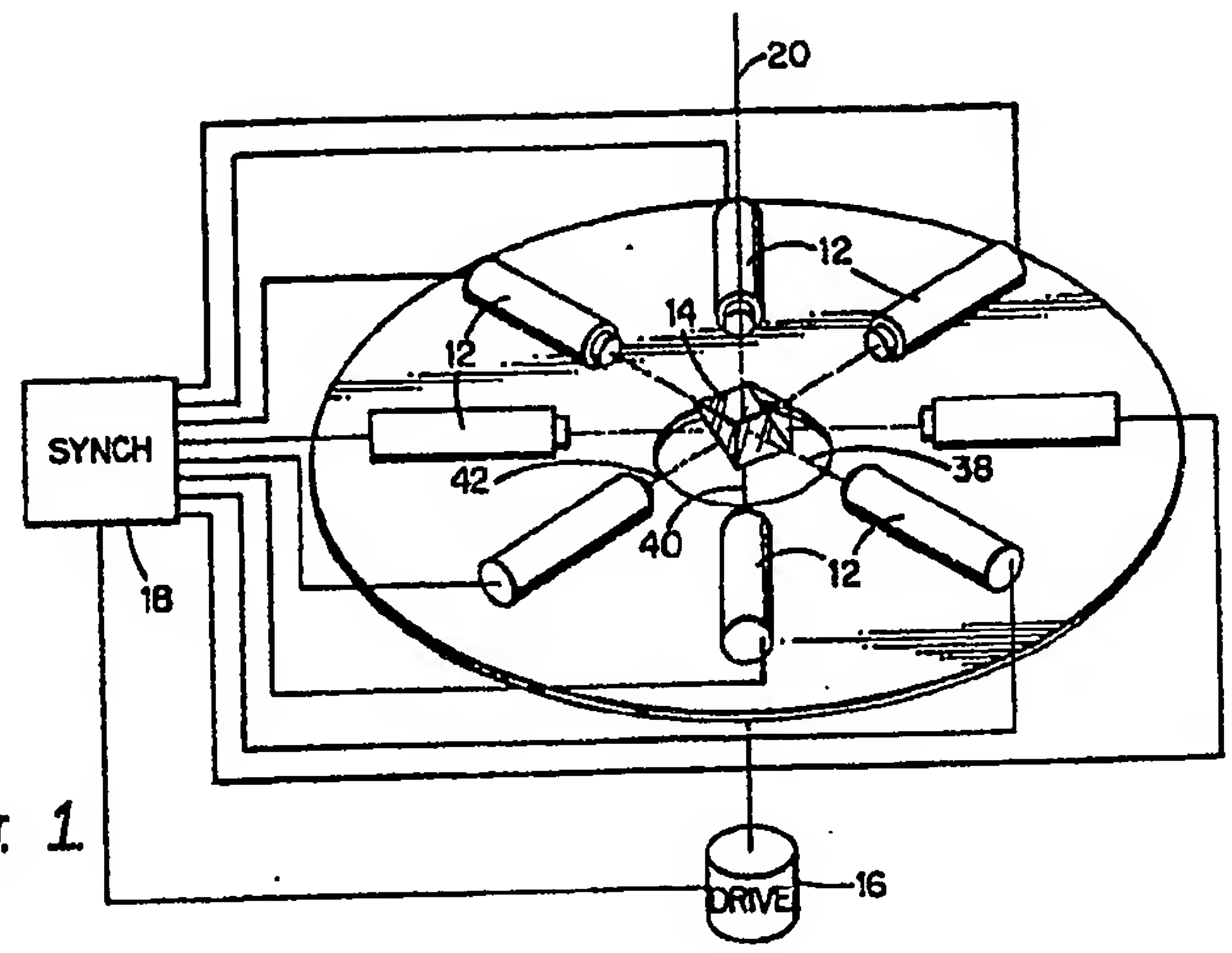

Fig. 1

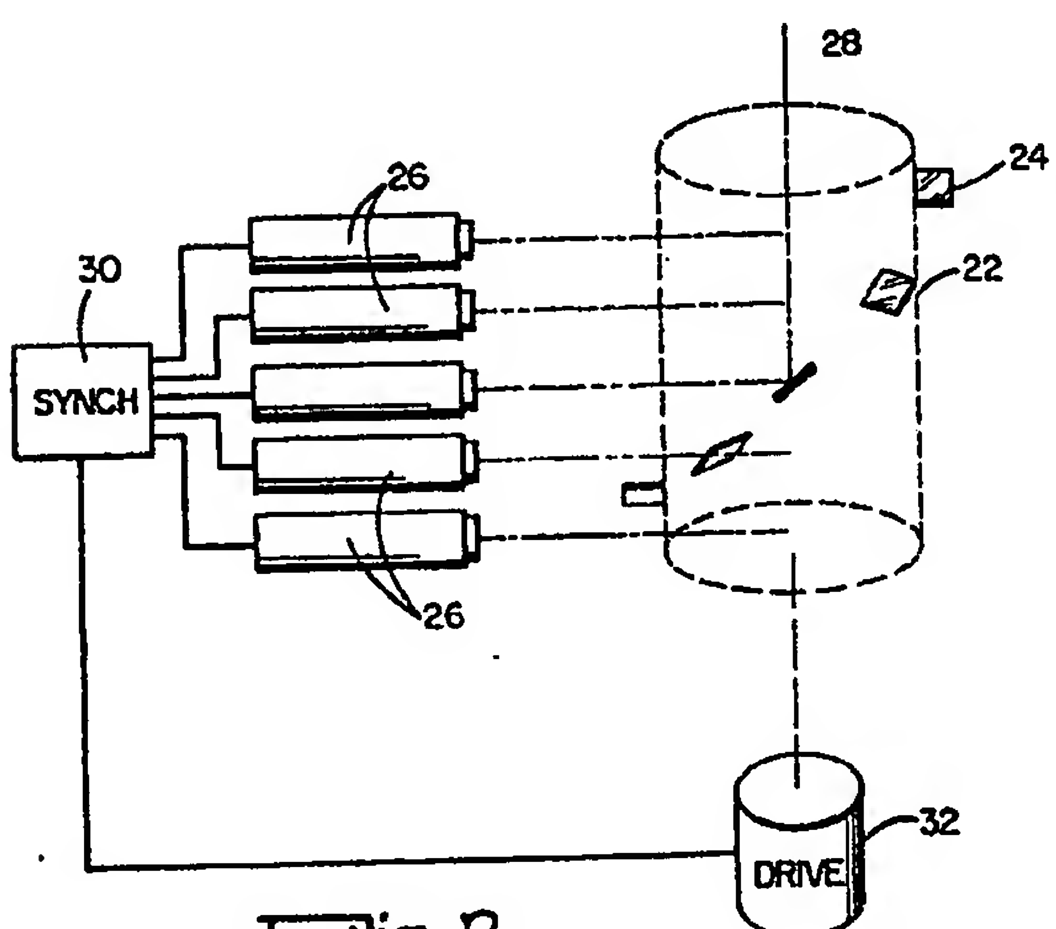

Fig. 2.

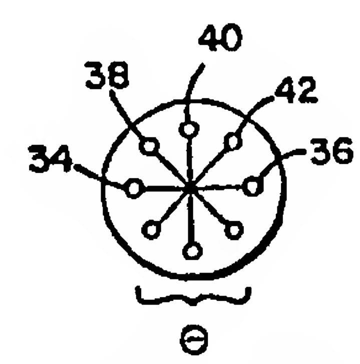

Fig. 3A.

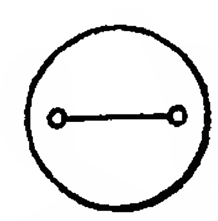

Fig. 3B.

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Sheet 2

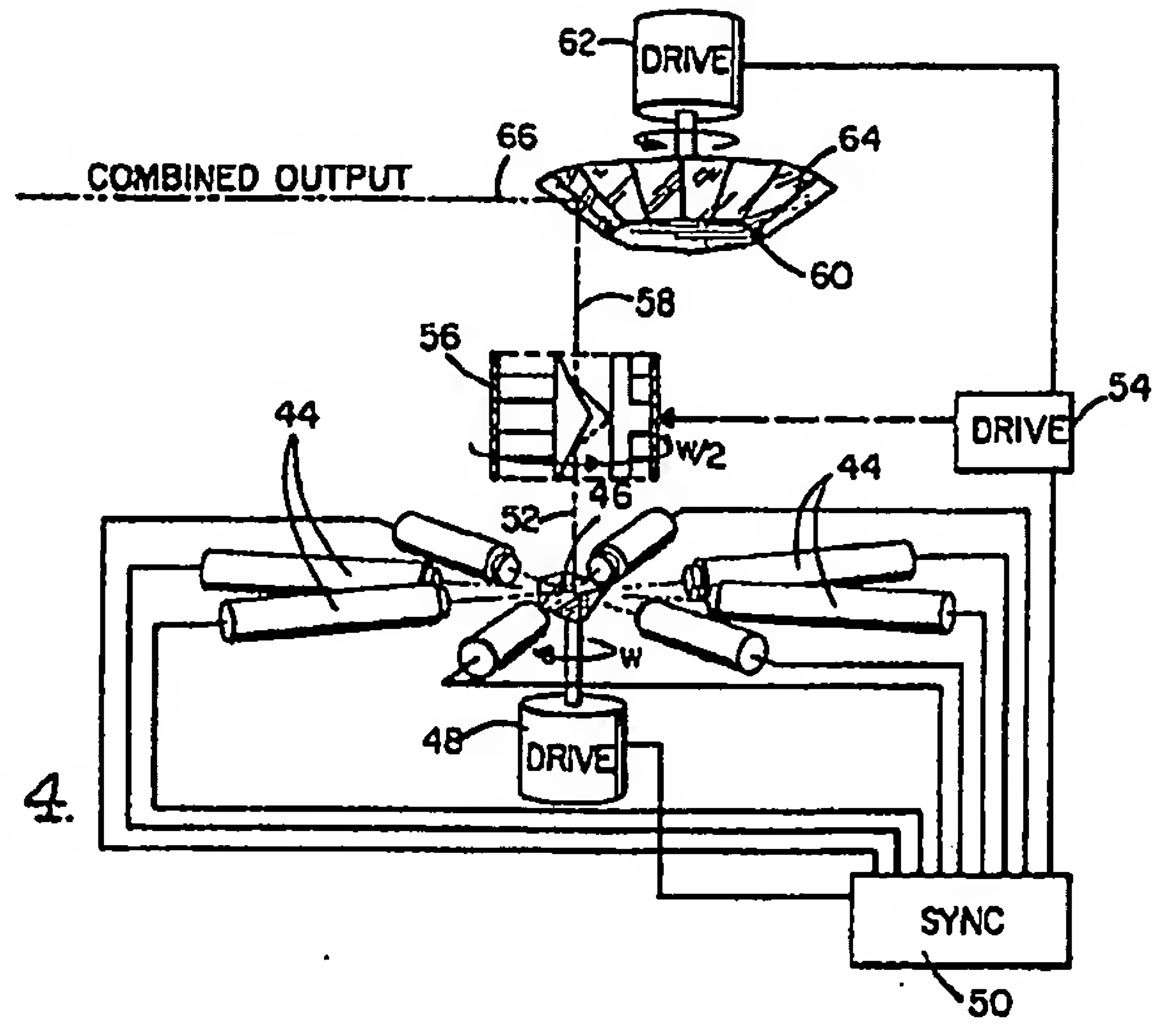

Fig. 4.

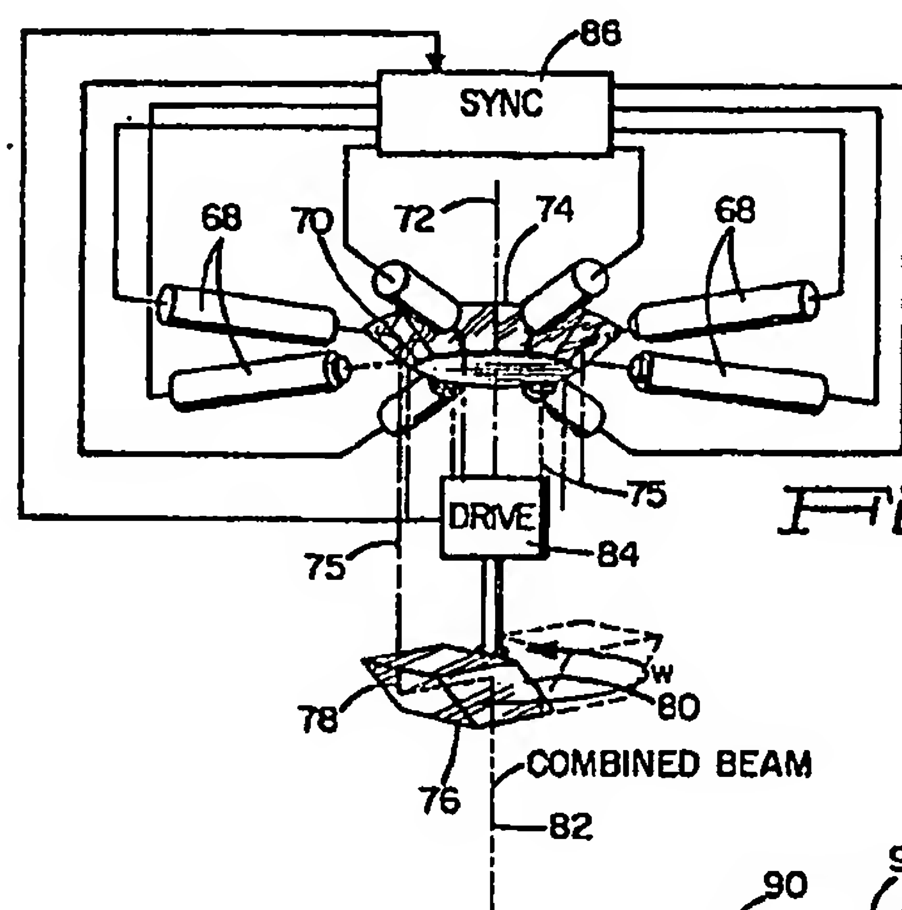

Fig. 5.

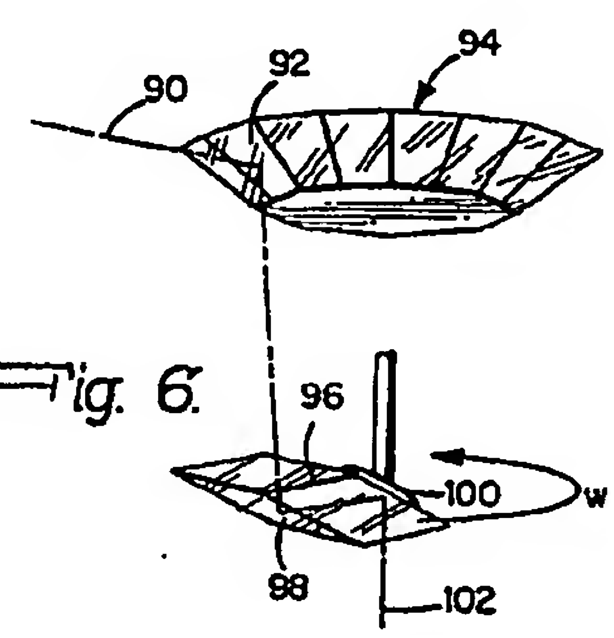

Fig. 6.

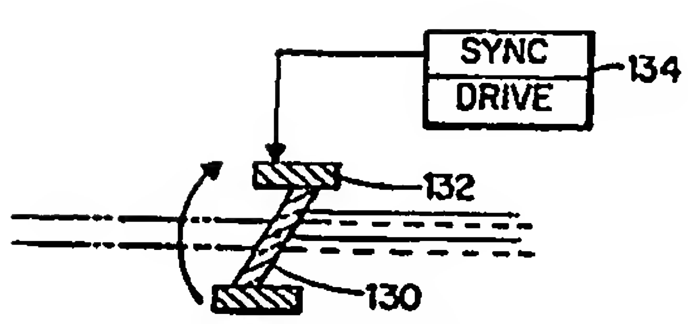

Fig. 9.

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Sheet 3

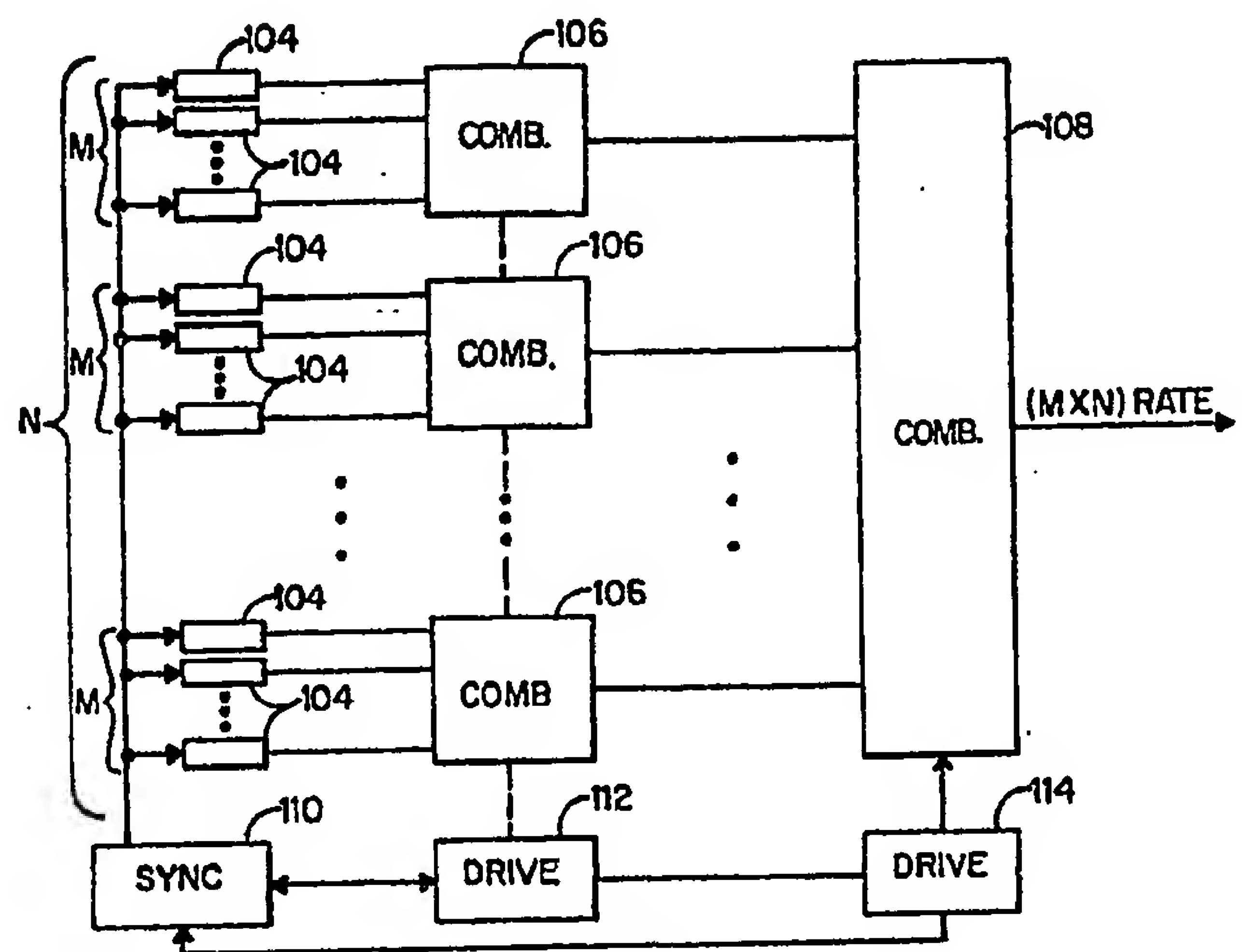

Fig. 7.

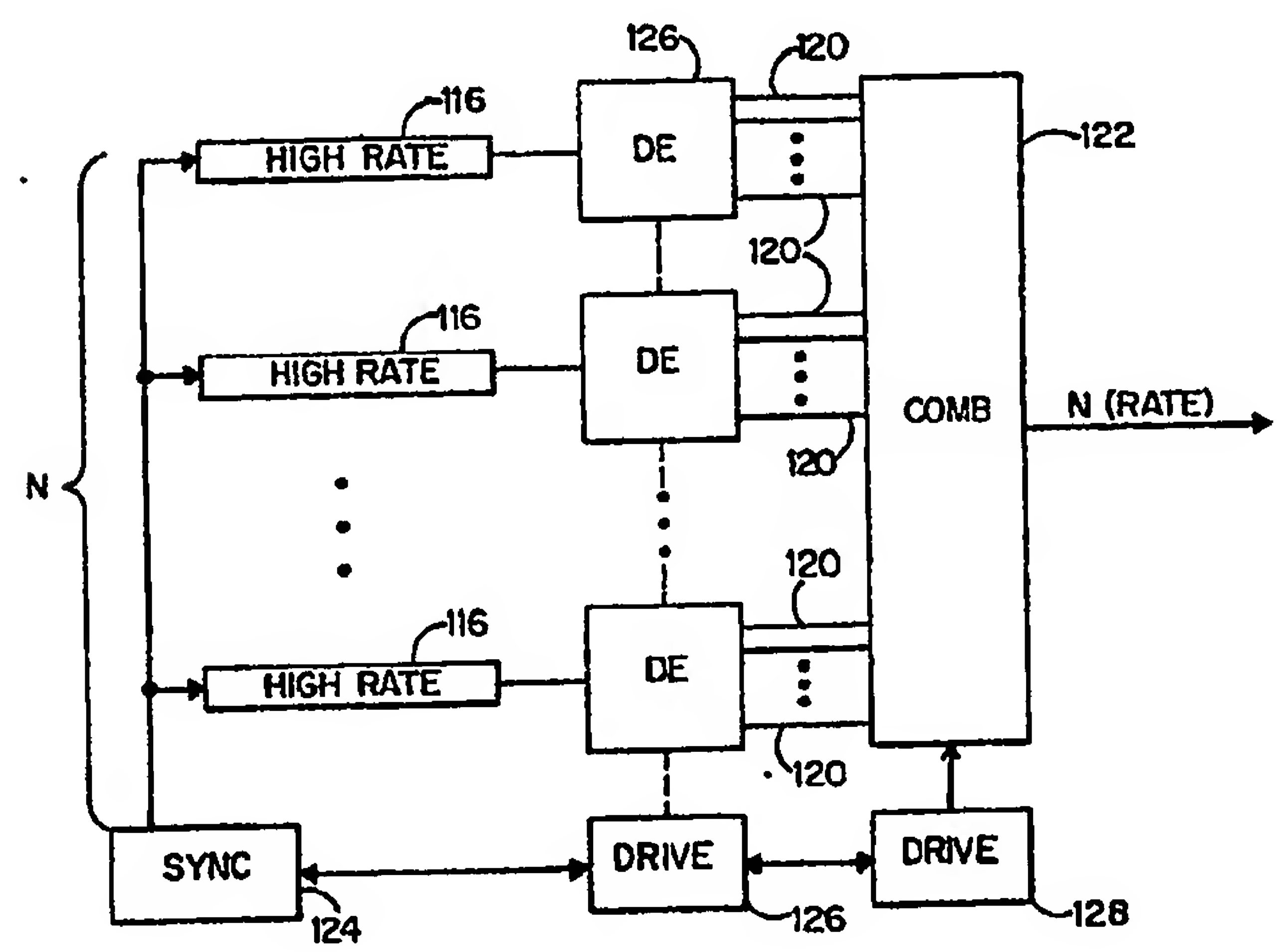

Fig. 8.